CHARACTERIZATION OF PERFORMANCE PREDICTORS AND EVALUATION OF MOWING PRACTICES IN BIOFILTRATION SWALES

Performed for

KING COUNTY LAND AND WATER RESOURCES DIVISION

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SNOHOMISH COUNTY ROAD MAINTENANCE

PIERCE COUNTY PUBLIC WORKS AND UTILITIES

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EXECUTIVE SUMMARY

PROJECT RATIONALE AND COVERAGE

The biofiltration swale is a common, flexible, and relatively low-cost option for treating stormwater. Biofiltration swales are shallow, relatively wide vegetated channels that remove pollutants through vegetative filtration and other mechanisms mediated by the plants and soil. Pollutant removal has been demonstrated to be dependent on the length of time (hydraulic residence time, HRT) that water remains in contact with fine, dense, uniform herbaceous vegetation and the soil surface.

Maintenance is important for keeping a well functioning swale; however, it is not always easy to tell how well a site is functioning and how much maintenance attention it should get. Swale performance can be assessed by measuring HRT, but doing so is time-consuming and not feasible as a diagnostic procedure for broad application. The first part of this study, therefore, attempted to develop a convenient method for evaluating performance by relating easily observed swale characteristics to HRT. Being able to evaluate a swale's status quickly, based on a few readily observable features, can permit specifying and prioritizing routine maintenance, as well as focusing renovation efforts on the sites that are likely performing the worst.

It is generally assumed that greater grass densities remove more pollutants, and that mowing promotes denser growth. Maintenance programs are frequently based on these assumptions, despite a lack of research to support them. It is important to know if they are valid, because mowing can take a large share of maintenance budgets. The second part of this study addressed this lack of information by examining the benefits of two mowing strategies in terms of measured pollutant removal. Knowing if mowing in general, or a particular way of mowing, benefits water quality can help guide future maintenance planning and allocation of funds to best advantage.

As with maintenance practices, there are uncertainties in swale design criteria; hence, performance may not match expectations. Without a ready alternative, design calculations often use Manning's open channel flow equation, even though it was developed for and applies best to fully turbulent flows that are deep relative to the channel features causing friction ("roughness"). In contrast, biofiltration swale flow should be at low turbulence and shallow, in close contact with the soil and dense plant stems, for the best treatment. Most problematic with Manning's equation is choosing the resistance coefficient ("Manning's n"). Analysis of the results from the first part of this study yielded new insights on this choice that will assist the design of future swales.

The full documentation for this study is contained in Colwell, S. R., 2000, *Characterization of performance predictors and evaluation of mowing practices in biofiltration swales*: University of Washington, Department of Civil and Environmental Engineering, Masters thesis, 104 p. It can be downloaded from the Center for Urban Water Resources Management's web page, **http://depts.washington.edu/cuwrm/**.

EXPERIMENTAL SITES AND METHODS

Performance Evaluation

The performance evaluation part of the study was conducted in 20 swales located in east, north, and south King County and representative of those constructed in residential subdivisions in the 1990s. These swales range in length from 57 to 222 ft, in width from 2.3 to 10.4 ft, and in surveyed longitudinal slope from 0.1 to 5.7 percent. All are trapezoidal in shape, but flows are generally very shallow compared to total swale depths. Most are associated with a stormwater pond, with nine of the 20 receiving pond effluent. About half have rip-rap for erosion prevention at the inlet, but only two have check dams for velocity regulation. The majority show signs of poor drainage, and four are extensively channelized.

HRT was measured in the spring of 1999, while swales were still saturated from winter runoff, by establishing a metered flow from a fire hydrant, targeting the ostensible design flow rate. Design rates were often not known with accuracy or could not be reached, and corrections were required later to allow comparison among swales. The test involved adding a fluorescent dye at the inlet and measuring with a fluorometer the dye concentrations at the outlet over time. Average HRT was taken as the centroid of the area under a curve of fluorescence versus time.

After completion of the HRT test and with the water still flowing, depth and width of flow were measured at 10- or 20-ft intervals, depending on the length of the swale. Depth was recorded at 0.5- or 1-ft intervals across the swale, depending on width.

Assessment of swale vegetation took place during the summer following the dye tests, when growing season development made full species identification possible. The assessment began with an inventory of the location and size of bare spots and extended bare channels. Species composition and relative cover (Daubenmire scale), as well as overall vegetation cover, were recorded in two, side-by-side 0.25 m^2 quadrats 10 meters from the inlet and then every 15 meters from the previous station. Areal coverages of each species and overall vegetation were computed from cover estimates and quadrat areas. Plant and organic litter biomass samples, as well as soil samples, were collected in each quadrat. Each swale was revisited in the spring of 2000, around the same time as the HRT tests the previous year, to note general spring vegetation cover and inventory bare spots and channels again.

Mowing Practices

This portion of the study was intended to investigate the water quality effects of two different mowing regimes commonly used or thought to offer benefits, both in comparison to an unmowed control: (1) mowing once in the summer growing season and once at the end of the growing season, to remove biomass before it released stored nutrients; and 2) mowing only once at the end of the growing season. Three separate swales similar enough in rainfall, geometry, vegetation, etc. could not be found. Therefore, a single large swale was divided in three equal parallel channels with plywood walls. This swale is in the Todd's Landing residential development, now within the City of Sammamish. It follows two detention ponds and is the final treatment before the stormwater is released into Pine Lake.

After installation of the plywood walls, the swale was left for a year to allow regrowth of damaged vegetation before sampling began. Meanwhile, a flow record was assembled to aid in programming monitoring equipment. Flows entering each channel were measured with V-notch weirs, in conjunction with ISCO flow meters. Outlet flows were assumed to be equal in each channel and were recombined for measurement with an H-flume and the same type of flow meter.

The first mowing was in early August 1999, when the swale had dried sufficiently after the relatively wet winter and spring. Vegetation in one channel was mowed to about 8 inches, the average height of flow when this swale was used in the HRT study. This channel and another one were mowed in late September 1999 to the same height. Following each mowing, the clippings were removed to the sides, from where drainage from them could not enter the swale. The third channel was not mowed.

ISCO samplers collected flow-proportional composite samples over 15 generally week-long periods from October 30, 1999 to March 14, 2000. Sampling extended for a week at a time, instead of just during individual storms, to give a comprehensive picture of treatment ability, incorporating both the long recession periods after rainfall ceased and base flows. Samples were analyzed for conductivity, turbidity, and period-mean concentrations (PMCs) of total suspended solids (TSS) and total phosphorus (TP). TSS and TP mass loading rates were calculated by multiplying each PMC by the associated flow volume and dividing by the number of sampling days.

PROJECT RESULTS

Performance Evaluation

Hydraulic Residence Time

Six of the 20 swales had site or test irregularities that substantially impacted the results. These swales were eliminated from consideration during analysis of the overall data. The remaining 14 swales were investigated to determine the deviation of test flow rates from realistic design values and the appropriate correction for comparing HRTs on a common basis. Design discharges were reestimated with Manning's equation and actual test data and used to estimate design flow velocities. The ratios of measured velocity:design velocity were then applied as scaling factors to estimate what HRTs would be expected at design flow rates (HRT_d). The procedure resulted in adjustments averaging 15 percent.

Test flow depths were all in the range 2.0 to 4.7 inches, and measured velocities ranged from 0.18 to 0.42 ft/second. Design velocity estimates were in a similar 0.15 to 0.51 ft/second range, and the HRT_d values estimated from them spanned 2.75 to 22.72 minutes. Only four swales, all with longitudinal slopes <1 percent, had HRT_d >9 minutes. In five swales HRT_d was under 5 minutes. Therefore, few swales in this representative set adhere to the preferred 9-minute residence time design criterion that was recommended after an earlier study in the region, and a number violate the minimum 5 minutes also recommended.

Manning's n values were computed from Manning's equation and measured values of flow rate, geometry, and slope. They range from 0.19 to 0.53, with a mean of 0.32 and a median of 0.28. The results overall are higher than the 0.20 value determined in a similar manner at one swale during the earlier study. There were no significant correlations between n and slope or vegetation cover, biomass, or species.

Vegetation Cover

The extent of spot bareness and channel bareness during the summer vegetation assessment varied between 0 and 96.7 percent and 0 and 54 percent, respectively. There were no statistically significant differences in these measures of cover among slope categories (<1.5, 1.5-2.5, and >2.5 percent). However, all four swales with slopes greater than 3.5 percent exhibited incision extending the full lengths of the channels.

Persistent saturation is often thought to be instrumental in poor vegetation cover and to be more of a problem in slightly sloping swales. Water was present during the summer in four of six swales with <1.5 percent slope, one of four within the 1.5-2.5 percent range, and two of four with >2.5 percent slope. Water in steeper swales generally appeared to be a result of continued base flow, while poor drainage usually explained water in flatter cases. Therefore, the study gives some support to the common belief.

None of the swales draining detention ponds showed major signs of erosion or channelization, but 35 percent had either flowing or standing water during the spring and 20 percent never dried out in the summer. In contrast, 45 percent of the swales not preceded by a pond had channelized areas. In this set 82 percent had flowing or standing water in the spring, and 45 percent contained water in the summer. Thus, it appears to be true, as often thought, that ponds preceding swales dampen the flow and reduce erosion. However, of the channelized swales not draining a pond, the three with the greatest degree of channelization also had slopes greater than 2.5 percent, suggesting that slope, not direct discharge, could be the primary cause of erosion. The other side of the argument suggests that placing ponds before swales can create long-term saturation conditions as the pond drains slowly. This theory is not well supported by the study, since a larger proportion of sites not draining ponds remained wet after winter runoff.

Overall summer vegetation cover ranged from 10 to 94 percent, with three of 14 swales having <50 percent and six   75 percent. Spring coverage, which probably better reflects wintertime conditions, fell in the same general range; but two more swales had <50 percent cover.

Swales with slopes between 1.5 and 2.5 percent retained cover most consistently between the spring and summer, with most sites at least 75-percent covered. All six swales with slopes <1.5% had spring cover less than 75 percent, with only two increasing cover above 75 percent in the summer. Only one of four swales with >2.5 % slope had cover >75 percent during both seasons; the other three fell below that level in both seasons. Statistically, cover was significantly greater in swales with 1.5-2.5 percent slopes compared to those with <1.5 percent slopes (summer and spring) and >2.5 percent slopes (spring only). The moderately sloping swales seem to escape some of the negative effects on cover created by persistent wetness in relatively flat channels and erosion in steeper ones.

The vegetation assessment recorded 53 different species over all sites. *Agrotis spp*. (bentgrass), *Holxus lanatus* (velvet grass), *Festuca arundinacea* (tall fescue), and *Ranunculus repens* (Buttercup) were most prevalent, occurring in 55, 26, 26, and 19 percent of the quadrats, respectively. *Agrotis spp.* appeared in 12 of 14 swales, and *R. repens* and *H. lanatus* were present in seven. *Agrotis spp*. covered the greatest percentage of the total area in the quadrats, 17 percent.

Relationships Among Measured Variables

A primary focus of this study was to identify readily observable factors that might be anticipated to control HRT, and thus influence swale performance. Obviously from kinematic relationships, HRT is a function of swale length and flow velocity. Data analysis showed slope to be the only other measured variable to have a significant relationship with HRT. No significant correlation was found between HRT and percent bare area, percent vegetation cover, above ground biomass, species richness, depth of flow, density of organic litter, or Manning's n. Therefore, the study results do not support the common assumption that vegetation density has a strong influence on HRT. It is impossible to infer from these findings the relative importance of time versus vegetation in regulating performance. Based on past results it is safe to conclude that the combination of long HRT and good vegetation cover should achieve the performance level previously demonstrated under these conditions, and that short HRT and poor vegetation cover will produce low pollutant reductions.

Statistical regression analyses were performed to investigate relationships that might be useful to assess HRT without the necessity of measuring it directly. This investigation yielded two equations that explain most of the variance in HRT, expressed as a fraction by R^2:

$$HRT = 0.025 L^{0.904} S^{-0.311} \qquad R^2 = 0.824 \qquad \text{Eq. ES-1}$$

$$HRT = 0.014\left(\frac{L}{V}\right)^{1.003} \qquad R^2 = 0.749 \qquad \text{Eq. ES-2}$$

where: HRT = Hydraulic residence time (minutes) L = Length (ft)
S = Slope (ft/ft) V = Velocity (ft/second)

Eq. ES-1 can be employed diagnostically to make an estimate of HRT after field measurement of swale length and surveying of slope. Eq. ES-2 is more applicable to design, where target values are specified for two of the variables and the third is calculated. These equations were developed from data spanning wide ranges of vegetation covers and types and should be quite broadly applicable.

Swale Design Considerations

The selection of a Manning's n value has been problematic in open channel flow design for more than a century. Many studies have shown it to vary with depth, especially in relatively shallow flows. Data from one swale in this study tested at two discharge rates confirmed this finding and, additionally, showed n to vary with flow rate and according to different slope assumptions.

With design made difficult without a constant n coefficient, the question arises on what is a reasonable and safe choice of a single value. Analysis performed in this work investigated the consequences of designing with numbers higher and lower than the "right" one. If n is too low, the swale width will be smaller than needed to carry design flow, resulting in increased depth, lower velocity, and longer length for a given HRT (or longer HRT for set length). Conversely, an excessive n will raise width and velocity and decrease depth and length for set HRT (or shorten HRT for specified length). The effects of over- and under-designing were evaluated according to sedimentation potential predicted from ideal settling theory and found not to differ much.

The conclusion was that, with n being uncertain, it is preferable from a water quality standpoint to over-design swale width as opposed to length (but only up to 10 ft wide, since this and other studies observed that flow does not distribute well over broad swales). This choice produces a shallower flow, making particle-settling distance shorter and putting water in greater contact with soil and the densest plant structures. The recommended choice for n is 0.30, close to the mean and median computed from the study's data, and higher than the 0.20 value from earlier research. A by-product of this analysis is a demonstration that, regardless of which value of n is chosen, a single swale can treat no more than roughly 1 cfs, depending on slope, and stay within the 10-ft maximum width and near a 3-inch flow depth.

Mowing Practices

TSS and TP mass loading rates for the influent and each channel effluent were computed in g/day for each sampling episode. Means did not differ significantly among channels for TP loading but did for TSS loading and turbidity, which was significantly lower in the unmowed channel than either of the mowed ones. Therefore, the experiment demonstrated no water quality advantage of mowing or of one mowing strategy over the other.

While the outcome of the experiment was conclusive, the test system may not be representative of all swales. First, vegetation other than grasses was prevalent and may not react to mowing the same as grass species. Second, influent concentrations of the measured water quality variables were very low, probably in large measure because of the upstream ponds (TSS ranged 0.9-17.2 mg/L with a mean of 2.9 mg/L, TP ranged 6.6-54.6 µg/L with a mean of 21.2 µg/L, and turbidity ranged 1.2-8.0 NTU with a mean of 2.6 NTU). They may not have been further reducible in the swale. In fact, the swale generally raised concentrations in all channels, although not to very high levels, and discharged higher loadings of TSS and TP than the total influent loadings in most sampling periods.

It has been thought that mowing promotes denser grass growth and reduces weeds that might shade out more desirable species. While vegetation cover, density, and species were not formally analyzed and compared among mowing treatments, there were no obvious visual differences. This aspect will be the subject of further study, with the continuation of the mowing regimes for two or more years and annual vegetation cover assessment. It was observed that growth in the control swale was not excessively high after a full year of no mowing, meaning mowing to contain overgrowth may not be necessary every year.

RECOMMENDATIONS FOR MANAGING SWALES TO IMPROVE WATER QUALITY

The following recommendations were drawn from the two portions of the project to guide assessment and maintenance of existing swales and design and construction of new ones.

Performance Assessment of Existing Swales

1. Each jurisdiction should measure lengths and survey all swales in its inventory to determine their average longitudinal slopes. Measurements should be repeated when swale configuration changes and every few years as a check.

2. Estimate the HRT of each swale with Eq. ES-1 and the measured slope and length.

3. Biannually, assess overall vegetation cover on a standard scale (e.g., Daubenmire) during or just after winter runoff. If possible, perform the assessment in side-by-side quadrats placed 10 meters from the inlet and then every 15 meters from the previous station.

4. Classify swales with HRT >9 minutes and vegetation cover >75 percent as well functioning and those with HRT <5 minutes and vegetation cover <25 percent as poorly functioning. Others likely have some but marginal function.

Maintenance Recommendations

1. For swales classified as well functioning, schedule routine maintenance as needed to retain their status, especially by removing deposits, minor grading to eradicate any channels that form, and revegetating bare spots.

2. For swales classified as poorly functioning, evaluate their importance for water quality objectives, problems, and potential to reach a relatively high functional level through major maintenance or renovation. Swales relied upon for water quality benefits and having a high potential for improved functioning should be scheduled for rehabilitation. Possible measures include:

    - Widening and/or lengthening to gain HRT;
    - Regrading to a more favorable slope (see Design and Construction Recommendations);

- Replanting with vegetation suitable for conditions, followed by an adequate establishment period before the swale receives unrestricted runoff; and
- Improving drainage by modifying soil and, possibly, installing an underdrain.

3. For swales considered to be intermediate in functioning, similarly evaluate their importance, problems, and potential to be upgraded through less extensive maintenance. Compared to poorly functioning swales, these facilities could be helped by smaller reconstruction, regrading, replanting, and/or drainage improvement projects.

4. Mowing strictly for water quality purposes cannot be recommended at this time in swales substantially populated by vegetation other than grasses. Mowing is still needed to prevent overgrowth and ascendance of woody species, and for aesthetics. If a highly "manicured" appearance is not necessary, mowing may only be necessary every 2-3 years. These recommendations do not apply to swales dominated by grasses, which should be specifically studied to develop appropriate mowing recommendations.

5. Use the savings from reduced mowing for rehabilitation of poorly functioning swales and upgrading marginal ones that are important to water quality protection and have a high potential for improved functioning.

<u>Design and Construction Recommendations</u>

1. Design swales with Manning's equation, using n = 0.30, for HRT 9 minutes. The design can be independently checked against Eq. ES-2 from this study.

2. Attempt to choose sites or grade to obtain longitudinal slope in the 1.5-2.5 percent range. Slope of this amount will increase velocity over that in swales placed at the typical <1.5 percent slope, meaning that length will have to be sufficient to meet the HRT criterion. If the slope must be steeper than 2.5 percent, install check dams to hold velocity to no more than that in the equivalent swale at 2.5 percent, or traverse to limit slope. If the slope must be <1.5 percent, plant wet-tolerant vegetation and consider improving drainage by soil amendment and, possibly, installing an underdrain.

3. Generally include *Agrostis spp.* in the planting mix. This plant has fine, dense blades and does well in most moisture conditions. While not native to the Puget Sound region, it should be part of the mix when runoff treatment is a primary objective.

4. Do not locate swales downstream of water quality treatment ponds. They can be placed after rate control ponds, which do not provide a treatment function themselves.